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Energetic Electrons at Synchronous Altitude 1967-1977

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17 July 1978

Interim Report

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This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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Data on energetic electron fluxes at the synchronous orbit, covering the 1967-1977 time interval, obtained by experiments flown on the ATS-1, ATS-5 and ATS-6 spacecraft have been combined. ~~We find that~~ The long-term averages of the fluxes of relativistic electrons at the synchronous orbit are relatively constant over this time interval, and flux variations correlate positively with averages of the solar wind velocity.

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PREFACE

We are grateful to Henry Hilton, Lee Christopher, Vera Bledsoe, Doretha Ross Mayfield, and Marie Wray for their assistance in data reduction and presentation. Al Vampola contributed several helpful suggestions. The scope of this work would have been limited without the generous offer of ATS-5 data by Carl McIlwain of UCSD and the interest shown by Jack Gosling of LASL. Any experimental study of the properties of the radiation belts over a span of more than a decade owes much to the skill and talents of the engineers who design and build the hardware. We are particularly grateful for the efforts of Sam Imamoto who participated with us in the ATS-1 and the ATS-6 projects.

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I. Introduction

The properties of the earth's radiation environment are known to be a function of the level of solar and magnetic activity when such properties are viewed both on long (months) as well as short (days) timescales (Refs. 1, 2). However only relatively few homogeneous data sets exist which trace the evolution of the trapped particle population in a particular region of the magnetosphere for a major fraction of the 11-year solar activity cycle. For example, Bostrom et al. (Ref. 3) followed the evolution of inner zone energetic electrons during the years 1963-1968, a time period including the decay of the Starfish-created artifical radiation belt. Filz and his colleagues (Ref. 4) have published a series of papers describing the changes which fluxes of inner-zone energetic protons undergo in response to changes in the source and loss functions which are governed by the 11-year cycle of solar activity.

In this paper we present a compilation of data which traces the history of the energetic electron fluxes at the synchronous altitude from 1967 to 1977. While the temporal coverage of this interval by data is not complete, we are able, nevertheless, to display the time history of the energetic electrons in an important region of the magnetosphere for virtually a complete cycle of solar activity. The data set is quite homogeneous, having been obtained by instrumentation with very similar physical characteristics. In addition, intercomparisons and normalizations between the several sets of data were possible, further homogenizing the data base. As a result, we can establish, with some confidence, absolute values of the electron flux over the time span under consideration and evaluate the variations of the electron flux in response to changes in the properties of the interplanetary medium. In this report we deal only with the long term behavior of the energetic electron population at the synchronous orbit. The day-to-day changes of the energetic electrons in response to changes in the properties of the solar wind and the interplanetary magnetic field are the subject of a separate study.

II. Description of Data

The data used in this report were acquired by sensors flown aboard several of the ATS series of spacecraft. Table I summarizes the time intervals of data acquisition as well as the locations of the spacecraft while in Figure 1 we superimpose the periods of data coverage on the usual measure of solar activity, the sunspot number. From Fig. 1, we see that the last maximum in solar activity occurred in 1969 and that the most recent minimum of the solar activity cycle has just occurred in 1976. Thus the combination of ATS-1, ATS-5 and ATS-6 data provides us a measurement of energetic electons at the synchronous orbit which spans the full interval from before the maximum of Cycle 20 to the beginning of Cycle 21.

The experiments on ATS-1 and ATS-6 were built by Aerospace. Descriptions of the details of an instrumentation can be found in References (2) and (5). The channels of data from these experiments used in this study were so chosen as to maximize our confidence in the absolute accuracy of the measurements and no normalizations or corrections were necessary, except as described in Section IV. For ATS-6, the basic data used were hourly averages of the electron flux which were used to compute daily flux averages above several energy thresholds. ATS-1 data with 40.96 second time resolution were used to compute the desired long-term averages.

The ATS-5 data of interest were obtained by an experiment, built by UCSD, which was similar in physical design and data characteristics to the ATS-1 and ATS-6 experiments. Shielded detectors were used to obtain measurements of omnidirectional energetic electron fluxes above several energy thresholds. The data were supplied to us (courtesy of Prof. C. E. McIlwain) in the form of daily average fluxes. Because the precise thresholds and geometric factors of the ATS-5 detectors are somewhat uncertain, we have chosen to normalize the energy channels of interest in the ATS-5 data set to the corresponding channels in ATS-6 data. This normalization was carried out by using the overlapping ATS-5 and ATS-6 data obtained in mid-1974, comparing all channels of ATS-5 data with each channel of ATS-6 data and normalizing to each ATS-6 channel that ATS-5 channel whose behavior most closely approximated the ATS-6 data. During mid-1974 ATS-6 was located at 94°W while ATS-5 was at 105°W, hence the comparison and normalization does not involve vastly different longitudes. The correspondence of channels and normalization factors for combining ATS-5 and ATS-6 data are given in Table II.

Table I: Locations of ATS Spacecraft

Spacecraft	Longitude (Deg.)	Approximate Mag. Lat. (Deg.)	Time Interval of Data
ATS-1	150°W	0°	Day 343, 1966 - Day 340, 1968; Limited Data in 1974, 1975, 1976
ATS-5	105°W	10°	Day 230, 1969 - Day 122, 1972 Limited Data in 1974
ATS-6	94°W	11°	Day 165, 1974 - Day 140, 1975
	In transit		Day 140, 1975 - Day 180, 1975
	35°E	0°	Day 180, 1975 - Day 214, 1976
	In transit		Day 214, 1976 - Day 330, 1976
	140°W	0°	Day 330, 1976 - present

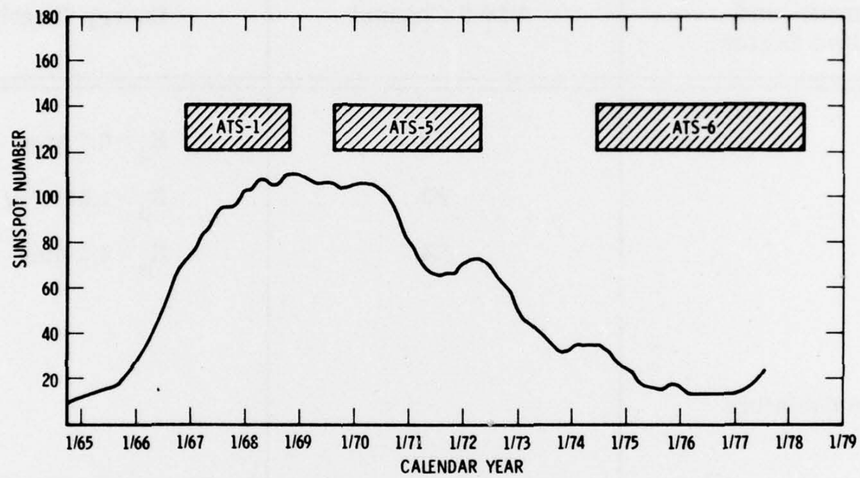

Figure 1. **Relationship between the intervals of acquisition of data on energetic electrons at synchronous altitude by experiments onboard ATS spacecraft and the solar activity cycle as defined by the Zurich sunspot number.**

Table II: Normalization of ATS-5 data to ATS-6 data

ATS-5 Channel* and Multiplicative Factor	ATS-6 Channel	Energy Threshold
1 A x 1.26	E2	$E_e > 0.7$ Mev
1 C x 1.54	E3	$E_e > 1.55$ Mev
2D x 1.24	E4	$E_e > 3.9$ Mev
*UCSD nomenclature		

As can be seen from Table I, the measurements of energetic electrons used in this report were obtained at several longitudes. Because the geomagnetic equator does not coincide everywhere with the geographic equator, the different longitudes of the various observations are equivalent to making observations at several magnetic latitudes. We have not corrected for the systematic flux differences which should be expected (Ref. 6), except as described in Section IV. However, a separate study to understand longitudinal flux variations using the ATS-1 data as the baseline, is in progress. Note that the normalization of the ATS-5 data to the ATS-6 data makes the observations from mid-1969 to early 1975 effectively self consistent. The ATS-1 data covering late 1966 to late 1968 and the ATS-6 data from mid 1975 to the end of 1977 were all obtained at the magnetic equator, except for the period Day 214, 1976 to Day 330, 1976. With these caveats, we expect that relative long-term changes in the energetic electron fluxes caused by changes in solar and magnetic activity can be unambiguously identified.

III. Energetic Electrons 1967-1977

Figure 2 summarizes the results. Shown in this figure are running 27-day electron flux averages as well as yearly flux averages (solid horizontal lines) obtained by the experiment on the ATS-1, -5, -6 spacecraft. Note that the ATS-1 energy channels (E_e > 1.05 Mev and E_e > 1.9 Mev) do not precisely correspond to the two lower ATS-5, ATS-6 Channels (E_e > 0.7 Mev, and E_e > 1.55 Mev). The monthly sunspot numbers have also been plotted to facilitate comparison of the observations with the phase of the solar activity cycle. The yearly flux averages for the 1969-1977 interval are separately summarized in Table III.

Several observations follow from an inspection of Figure 2:

1. The general behavior of energetic electron fluxes at the synchronous altitude does not change significantly as a function of solar activity: the range of the 27-day running averages as well as the range of the yearly averages is similar during periods of maximum sunspot numbers as well as during near-minimum sunspot conditions.

2. The excursions in the flux associated with the 27-day solar rotation period exceed by far the range of the long-term variation of the electron fluxes.

3. The yearly flux averages are in general relatively constant, apparently almost independent of the phase of the cycle of solar activity and any changes in the geometry of the trapping zones, (see Ref. 7, 8, 9) which might be induced by gross changes in solar activity.

4. The energetic particle fluxes appeared to be anomalously high during 1974, 1975 and early 1976. This apparent "anomaly" appears to be connected with the very high solar wind velocities which were observed in interplanetary space during this time interval. The correlation between the average properties of the solar wind and the long-term average electron fluxes are discussed in Section IV, below.

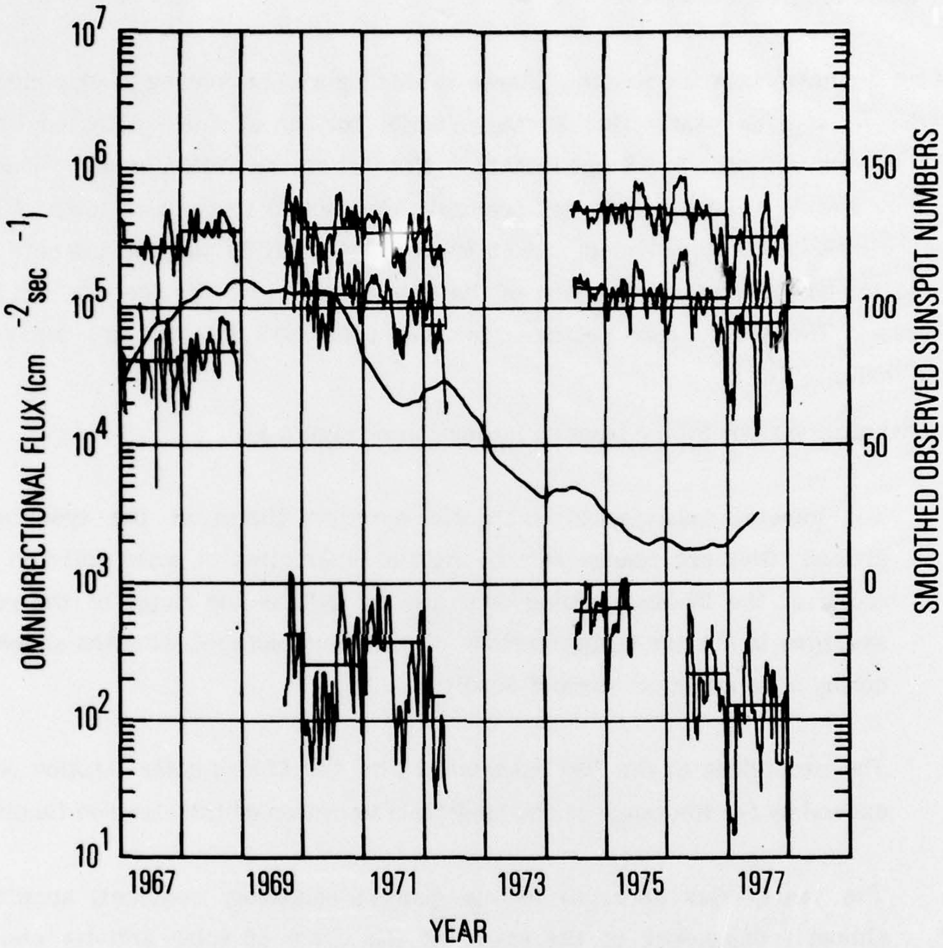

Figure 2. ATS-1, ATS-5 and ATS-6 energetic electron fluxes (running 27 day averages) as a function of time (see Table I for details of time coverage). ATS-6 and ATS-5 data are superimposed in mid 1974. The energy thresholds for the ATS-5 and ATS-6 channels are >0.7 Mev, >1.55 Mev and >3.9 Mev, from top to bottom, respectively. The ATS-1 thresholds are E_e > 1.05 Mev and E_e > 1.9 Mev. The flux averages for each year are also indicated (solid horizontal lines). Superimposed on this graph is the Zurich monthly sunspot number, referred to the linear scale on the right.

Table III: Flux Averages: ATS-5 and ATS-6 Data

	ATS-5†				ATS-6			
Year	No. of days	"E2" >0.7 Mev	"E3" >1.55 MeV	"E4" >3.9 MeV	No. of days	E2 >0.7 MeV	E3 >1.55 MeV	E4 >3.9 MeV
1969	133	5.05E5	2.06E5	4.21E2	–	–	–	–
1970	362	3.78E5	1.29E5	2.49E2	–	–	–	–
1971	364	3.58E5	1.13E5	3.72E2	–	–	–	–
1972	122	2.56E5	7.29E4	1.15E2	–	–	–	–
1973	–	–	–	–	–	–	–	–
1974	48	5.67E5	1.58E5	5.34E2	196	5.03E5	1.36E5	6.21E2
1975	–	–	–	–	362*	5.10E5	1.25E5	6.46E2
1976	–	–	–	–	343**	4.91E5	1.18E5	2.15E2
1977	–	–	–	–	331	3.18E5	7.61E4	1.27E2

† ATS-5 Channels Normalized to ATS-6 (Table II)

*E4, 139 days only

**E4, 235 days only

IV. Correlation of Electron Flux Averages with Solar Wind Velocity Averages

It is of considerable interest to determine whether there exists a quantitative relationship between long-term flux averages of energetic electrons and long-term averages of, say, the solar wind velocity or perhaps some other parameter describing solar activity. A study relating the connection between long term (semiannual) averages of the solar wind velocity and geomagnetic activity has recently been reported by Crooker et al. (Ref. 10).

From inspection of Fig. 2 we can already say that the properties of the energetic electron radiation at the synchronous orbit do not follow the cycle of solar activity as described by the sunspot number. Such changes in the average flux as occur can be seen to be rather undramatic especially when viewed on a semi-log scale. The relative lack of variability suggests that correlation of average electron fluxes with the average solar wind velocity might be fruitfully pursued. Using the semiannual averages of the solar wind velocity cited in Crooker et al., as well as more recent data graciously provided to us by Jack Gosling, we obtain Figs. 3a, 4a and 5a which presents a plot of semiannual averages electron flux as a function of the (semiannual) average velocity of the solar wind. Figures 3b, 4b and 5b show electron averages as a function of the square of the velocity, following the work of Crooker et al. who found that the magnetic activity index A_p correlates with V_{SW}^2. In constructing Figs. 3, 4 and 5, we have used only ATS-5 and ATS-6 data. This data set is the most homogeneous*, having normalized as described in Section II. In addition, all ATS-5 data and the ATS-6 data to Day 140, 1975 were multiplied by a factor of 1.5 in order to convert the measurements made before that date at about 11° magnetic latitude to equivalent equatorial fluxes.

The results shown in Figures 3, 4 and 5 suggest a rather strong dependence of the electron flux on the solar wind velocity, modified however, by a hint that flux saturation effects or changes in the geometry of the region of stable trapping under the impact of very

*Our experience to date has shown that it is virtually impossible to make absolute flux measurements to accuracies better than ≈ 20%. Because the variations in the long term flux averages are relatively small, absolute calibration uncertainties of different instruments of the 20% level become significant for quantitative correlations. Having not yet normalized the ATS-1 data to the ATS-5, ATS-6 data set, we felt justified in using only the later data for the present correlation study.

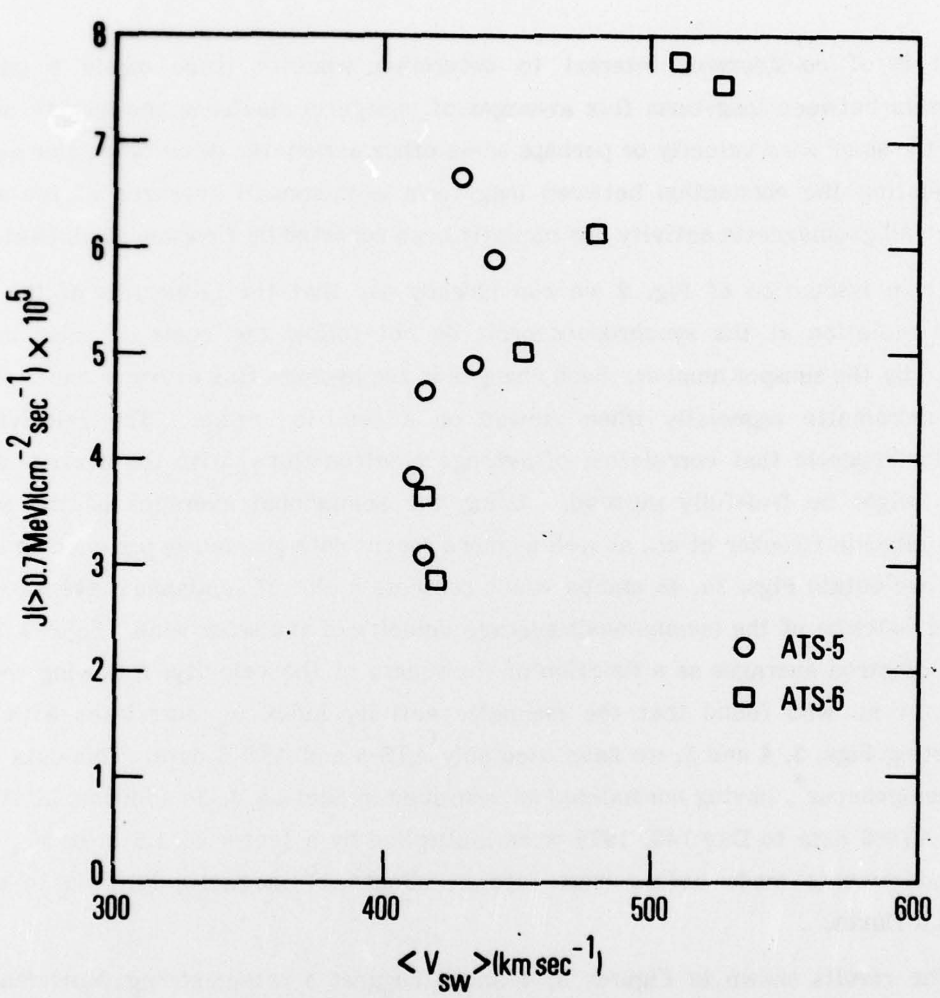

Figure 3a. **Plot of the semi-annual average of the E_e > 0.7 MeV electron flux as a function of the semi annual average of the solar wind velocity. ATS-5 and ATS-6 data are included in this plot.**

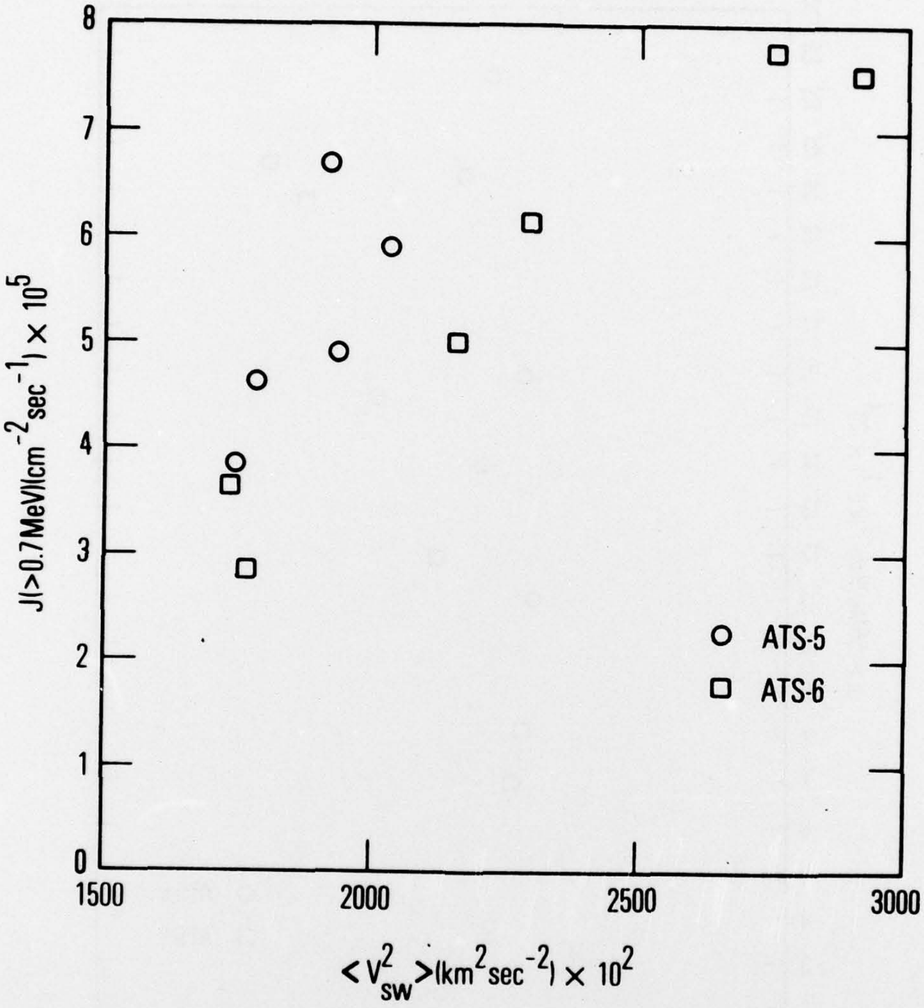

Figure 3b. Plot of the semi-annual average of the E_e > 0.7 MeV electron flux as a function of the average of the square of the solar wind velocity. ATS-5 and ATS-6 data are included in this plot.

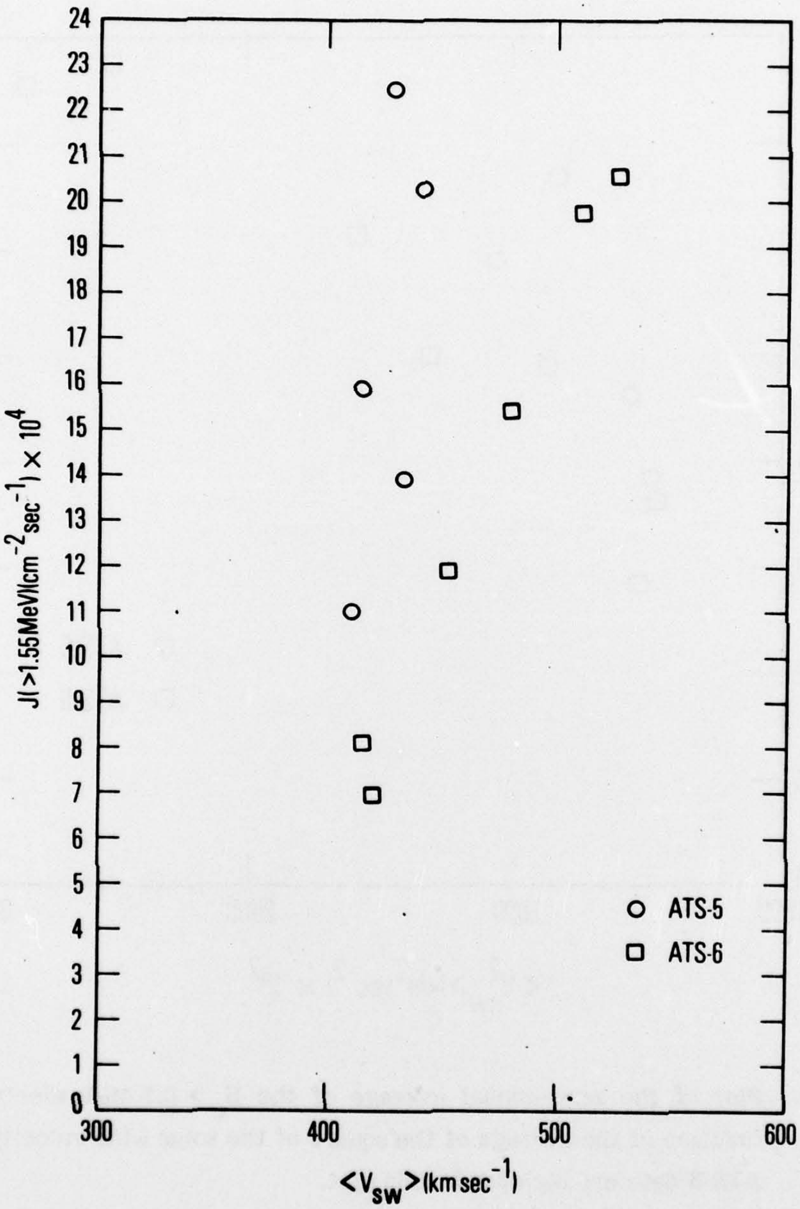

Figure 4a. **Same as Figure 3a, except that E_e > 1.55 MeV.**

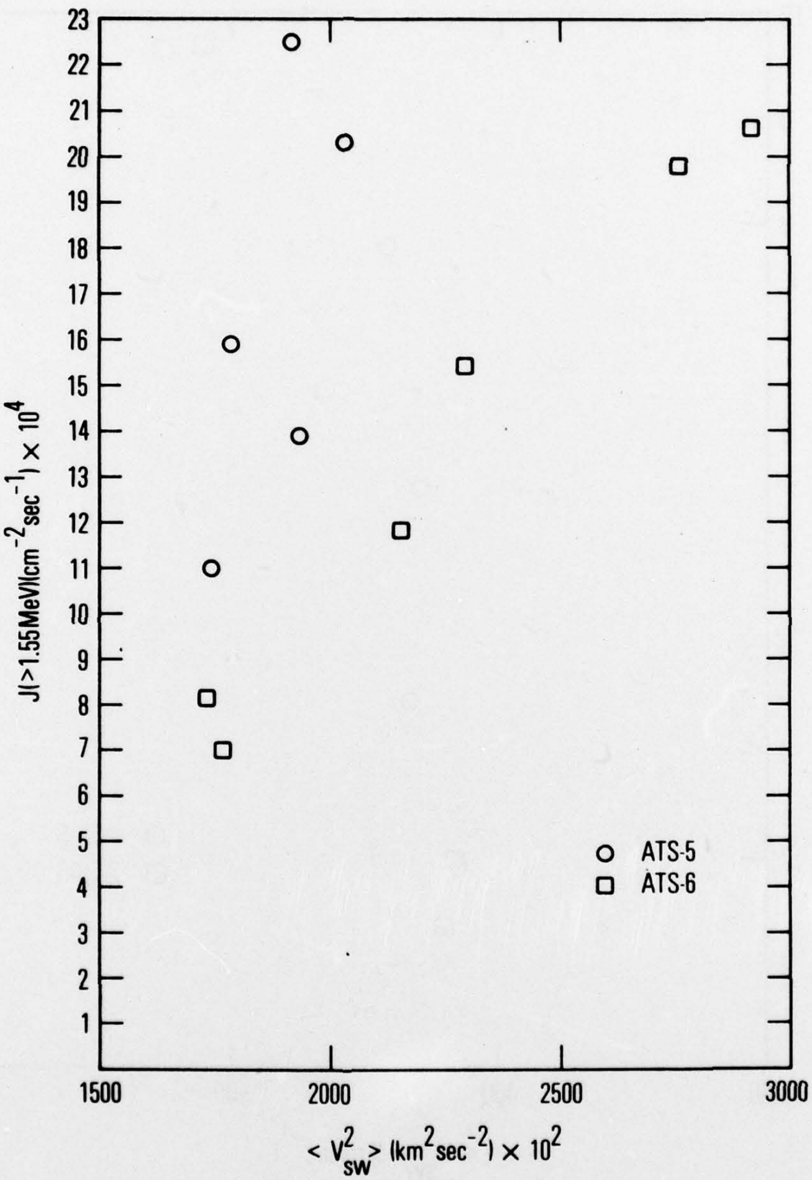

Figure 4b. **Same as Figure 3b, except that E_e > 1.55 MeV.**

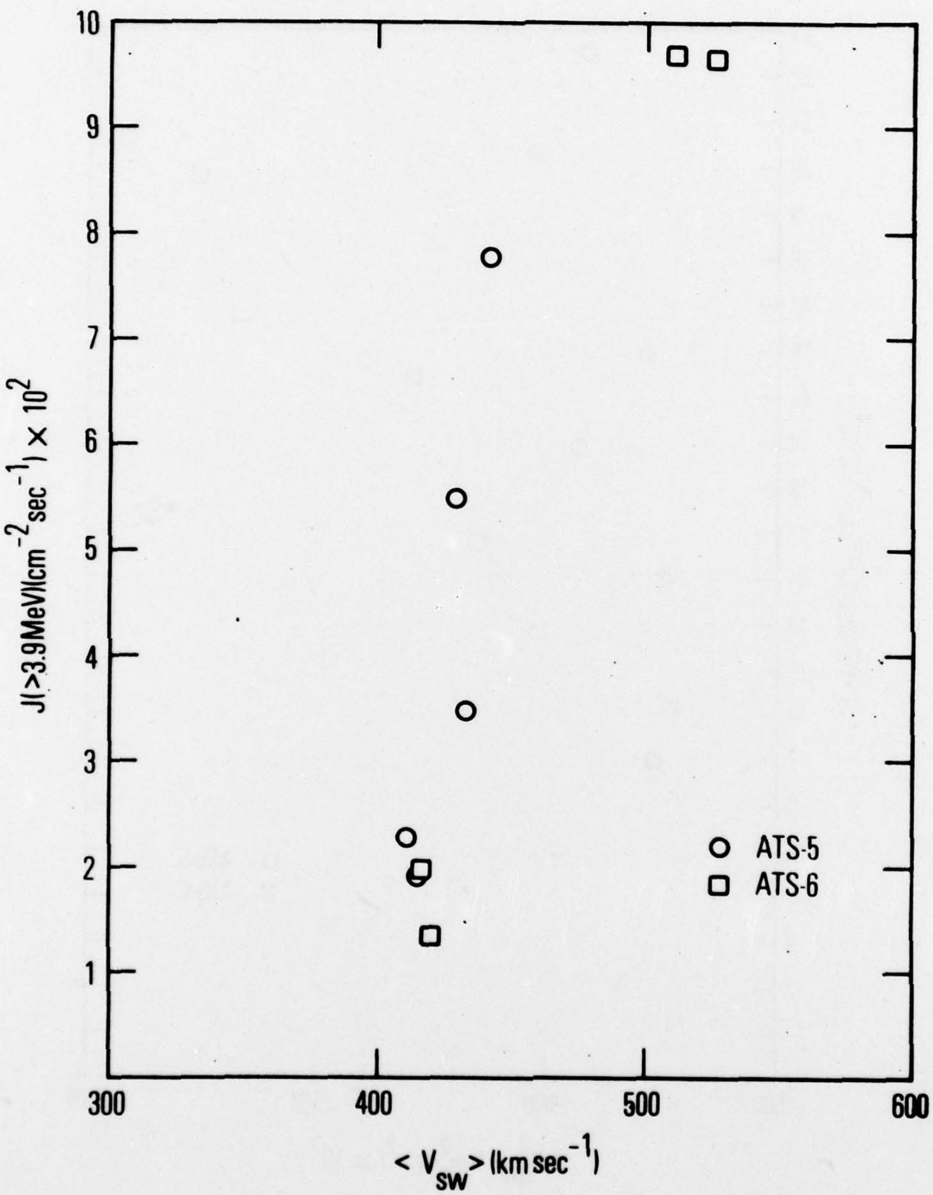

Figure 5a. **Same as Figure 3a, except that E_e > 3.9 MeV.**

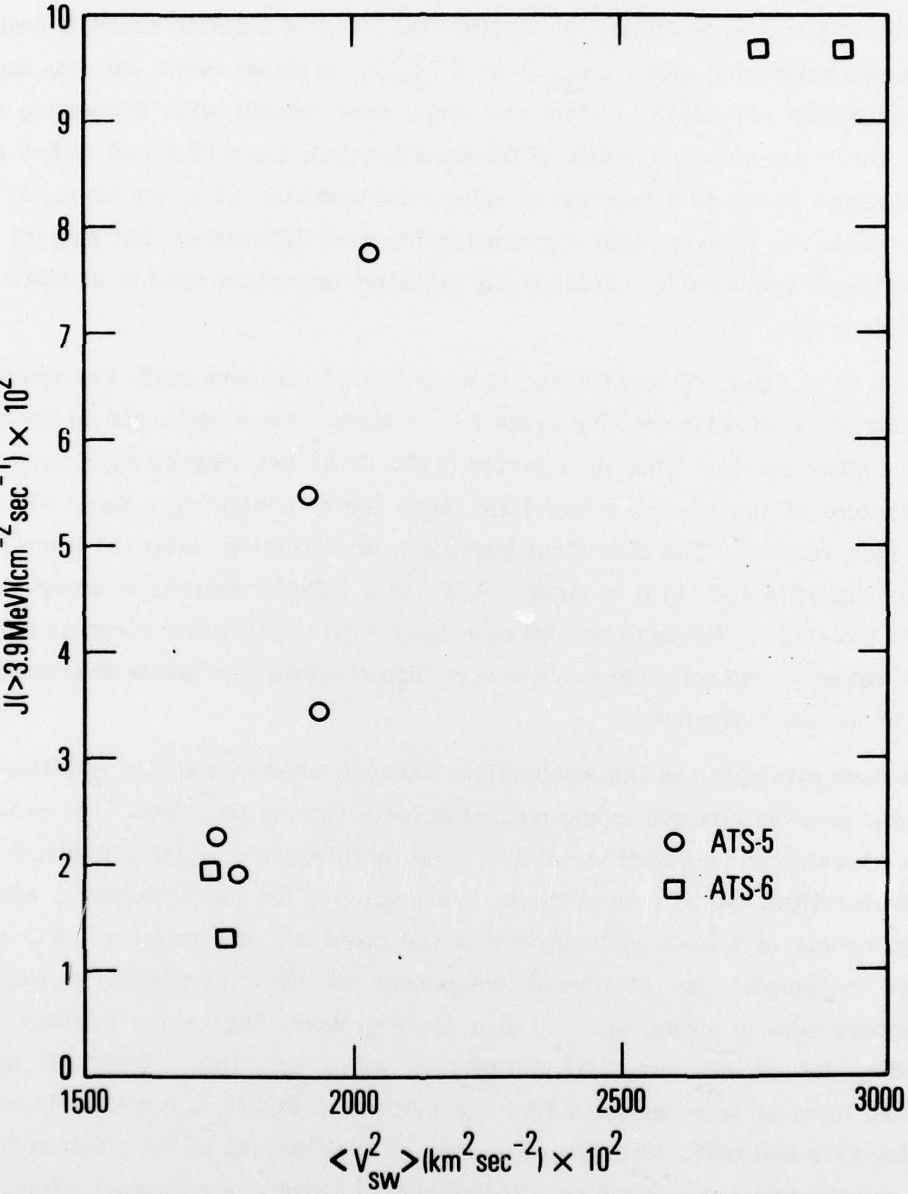

Figure 5b. **Same as Figure 3b, except that E_e > 3.9 MeV.**

high solar wind velocities limit the ultimate flux levels which can be reached. There is too much scatter in our data to distinguish whether the trend of electron fluxes is best predicted by the average solar wind speed $\langle V_{SW} \rangle$ or $\langle V_{SW}^2 \rangle$. In either event, our data suggests that rate of generation of energetic electrons drops very rapidly with decreasing solar wind velocity. There are also systematic differences between the ATS-5 and ATS-6 data in the trend of electron fluxes as a function of solar wind velocity. (See, for example, Figures 4a and 4b.) We do not have a ready explanation for such differences, but suspect that these might be artifacts produced by our relatively primitive techniques used to combine the ATS-5 and ATS-6 data sets.

Bame et al. (Ref. 11) and Gosling et al. (Refs. 12, 13) have made the observation that the declining phase of solar activity Cycle 20 is different when compared to the same phase of previous solar cycles. This time period (1973-1975) was marked by a very stable two sector structure of the interplanetary field, each sector containing a solar wind stream of unusually high velocity. The anomalous interplanetary situation yields the three highest flux data points (for 1974 and 1975) in Figures 3, 4 and 5. The downtrend in energetic electrons since mid-1976 (Fig. 2) seems to be well correlated with a systematic decrease in the average solar wind velocity. We conclude that the very high electron flux levels observed in 1974 and 1975 are an unusual phenomenon.

We have attempted to find connections between some of the flux variations evident in Figure 2 and possible changes in the magnetospheric forcing functions. For example, there exists a well-known semi-annual variability in magnetic activity which is explained by Russell and McPherron (Ref. 14) as caused by the orientation of the magnetosphere, which changes during the course of a year with respect to the interplanetary medium. This variation of orientation maximizes the southward component of the interplanetary field that the magnetosphere sees in spring and fall thus leading, according to the standard theories of reconnection, to enhance magnetic activity in spring and fall. With the aid of some imagination, hints of semi-annual effect are evident in Figure 2, particularly in the ATS-6 data set for 1976 and 1977. Note the occurence of deep minima in the electron flux near the solstices and the relative maxima near the equinoxes. Such a semi-annual effect, if it exists, is clearly of lesser importance in governing the electron flux levels than the variablity of the fluxes caused by the very different characteristics of successive solar rotations.

We have also searched for a correlation between electron flux levels and transitions in the interplanetary field from two sector structures to a four sector structure and conversely. This idea stems from the fact that the flux decrease beginning in mid 1976 was more or less coincident with a transition from a two sector IMF to a four sector IMF. Physically, we might expect that the relatively rapid "oscillation" in the IMF the four-sector mode, as seen by the magnetosphere, coupled with the finite generation time of energetic electrons, might inhibit the buildup of fluxes. Examination of the IMF structure catalog prepared by Svalgaard (Ref. 15) revealed several other transitions between a two sector and a four sector IMF structure occurred during the time period spanned by our data. Comparison of these times of occurrence with the data presented in Fig. 2 does not lead to unambiguous correlations. We are of the opinion that the average velocity of the solar wind, rather than the details of the IMF sector structure exerts a governing influence on the long term averages of energetic electron fluxes in the outer magnetosphere. Thus techniques which could predict the occurrence and persistence of high-speed solar wind streams should be of unquestionable value in predicting the levels of energetic electron fluxes in the outer magnetosphere.

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